Regime Shifts in U.S. Inflation Persistence
and
the Lucas Critique

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Abstract

We highlight changes in the U.S. inflation dynamics to find out if regime shifts in inflation persistence since 1960 can be explained by the Lucas Critique. In particular, we estimate a state-space model with Markov-switching to detect the characteristics of the inflation dynamics and investigate the regime change points. Our approach indicates that inflation persistence increased considerably after the collapse of the Bretton Woods system and decreased since the beginning of the Volker-Greenspan era. These findings imply that, of the multilateral causes which accounted for those changes in U.S. inflation persistence, the Lucas Critique is an essential explanatory factor.

JEL classification: C22, E31

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1. Introduction

Reducing inflation inevitably entails costs such as depressing output or slashing employment in society. One of the main factors that make it impossible to bring down inflation without cost is inflation persistence, as often referred to in existing literatures[1]. The more persistent the inflation, the costlier disinflation. Therefore, it is implied that relentless inflation persistence requires even harsher monetary policies to bring down inflation, at the same time causing more sacrifices in output[2]. The reduction in the degree of persistence is associated with the steepness of the Phillips curve, which is why U.S. inflation persistence has received substantial attention.

In this sense, it is considerably important to investigate if U.S. inflation dynamics, particularly the extent of U.S. inflation persistence, has changed over time. It is also necessary to examine what has played a key role in determining the regime changes in U.S. inflation persistence[3].

With regard to regime changes in U.S. inflation persistence, there exist multilateral views in the empirical studies. Firstly, Kim (2000) found evidence that in the postwar period 1948:II-1994:I, the U.S. inflation rate underwent regime switching from stationarity to non-stationarity around 1973:III. Leybourne, Kim and Newbold (2003), however, suggested an estimation result that the U.S. inflation changed from I(1) to I(0) around observation 1982:II, using tests designed to detect changes in persistence of a time series from difference stationarity to trend stationarity,

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[1] Buiter and Jewitt (1981) first explained the costly disinflation with sticky-inflation model and Fuhrer and Moore (1995) suggested consistent theoretical and empirical results. On the other hand, Roberts (1997) presented the somewhat different view that inflation was not sticky and that inflation expectations were less than perfectly rational, which caused the inflation persistence.

[2] Through simulation, Fuhrer (1995) showed that when the inflation is persistent, the output loss associated with disinflation is more considerable than when it isn't. As another implication, it was found that the key factor in the yield curve's predictability to output growth is the persistence of inflation. Bordo and Haubrich (2004) provided theoretical and empirical evidence that the yield curve had better predictability in regimes with high persistence of inflation.

[3] On the other hand, Levin and Piger (2003), after analyzing the dynamics of inflation for twelve industrial countries over the period 1984-2003, presented evidence that high inflation persistence is not an inherent characteristic of industrial countries, including the United States.

or vice versa, for the period 1959:I-2000:IV. The difference in results between the two studies lies in the fact that Kim's (2000) test was taken against the single alternative of I(0) changing to I(1), while Leybourne, Kim and Newbold (2003) analyzed the inflation dynamics without prior knowledge of the direction of the change. But both of these approaches have the crucial limitation of assuming just a single unknown break point. Nevertheless, we notice the fact that their different estimation results actually show the possibility of double structural breaks in the inflation process. This possibility is supported by other studies.

Benati (2002) reported empirical evidence that U.S. inflation experienced higher persistence after the mid-1960s and fell again from the beginning of the Volker disinflation, from the estimation of the random-coefficients autoregressive model with GARCH. In addition, Evans and Wachtel (1993), from estimation results of a Markov-switching model with two states, random walk and AR(1) process, discussed that U.S. inflation persistence dramatically increased in the late 1970s and fell again in the mid-1980s. Although their model allowed for the observed heteroskedasticity of forecasting error and unknown regime change points, they imposed the extreme restriction that the inflation process shifted between a random walk and a purely stationary process. It was also assumed that the inflation dynamics before the late 1970s were identical with those after 1985. However, persistence and unconditional mean are likely to be significantly different between the two periods, as Bleany (2000) supports.

Alogoskoufis and Smith (1991, henceforth A-S) argued that U.S. inflation persistence changed in the late 1960s for the period 1948-1987, by estimating AR(1) coefficients for the annual change in the GDP deflator. However, Burdekin and Siklos (1999, henceforth B-S) pointed out that A-S's (2000) inflation equation is inadequate for the U.S. data by showing the significant serial correlation of residuals. B-S (1999) also argued that after 1950, the only significant break in U.S. inflation persistence was estimated at 1979, when applying the Perron and Vogelsang (1992)

procedure to the annual CPI .[4] But the validity of the B-S framework for the inflation persistence tests is questionable because the heteroskedasticity of residuals was not considered in the econometric model, even if the serial correlation in residuals was controlled. The existence of the heteroskedasticity is strongly supported by the estimation results in this paper. Bleany (2001) also found that there was a significant upward shift in persistence in 1973-1983, based on annual observations of consumer prices for United States. In that the structural break points were assumed to be known, Bleany's (2001) empirical methodology held a limitation.

The main aim of this paper, using an econometric model, is to characterize U.S. inflation dynamics focusing on changes in persistence. We will then discuss the fact that our estimation results support the previously-established theoretical outcome that the exchange rate system and monetary policy regime played a significant role in determining the extent of inflation persistence. We will employ a state-space model with Markov-switching to investigate shifts in inflation persistence across exchange rate systems and monetary policy regimes with the prior knowledge that since 1960, there have been three kinds of regimes in U.S. inflation dynamics. The main features of our models are that they allow the heteroskedasticity in prediction error and at least two structural changes in inflation dynamics without the restriction that inflation must follow a purely stationary process in a state. After the transformation of the basic model into its corresponding form of a conventional ARIMA model, we will verify the difference in the extent of the inflation persistence across the three regimes by estimating the cumulative impulse response function for each state.

By estimating the probability of regime change and structural break in U.S. inflation dynamics under unknown break date, we will come to a conclusion about whether or not the

[4] In addition, Papadopoulos and Sidiropoulos (2000) suggested break points for the selected EMU countries' inflation persistence, based on Perron (1997) where the null hypothesis of a unit root is set against the alternative of stationary about a single broken trend.

Lucas Critique can explain the historical findings that inflation persistence has changed over time.

Through the estimation of the state-space model with Markov-switching, we will conclude that the shifts in the persistence of U.S. inflation not only existed, but that they also coincided with the regime changes in both exchange rate systems and monetary policy operations. Specifically in postwar United States, there were two instances which caused significant shifts in the persistence of inflation rate. The first was the abandonment of the international fixed exchange rates regime under the Bretton Woods system in the late 1960's. The second was the monetary policy rule change after Paul Volker under the flexible rate system. Thus, our empirical evidence supports A-S's(1991) conclusion that economy agents are forward-looking price-setters under price stickiness, which is definitely consistent with the Lucas Critique.

This paper is organized as follows. Section 2 discusses the model specification we used to detect changes in U.S. inflation dynamics. Section 3 reports and illustrates the empirical evidence and the estimation results of the regime change points. Section 4 discusses the nature of the regime shifts in inflation persistence. Finally, Section 5 summarizes our conclusions.

2. Model Specification

We will consider the following regime-switching state-space model with three states, first order Markov-switching process for S_t, which is discrete-valued, unobserved and evolves according to the transition probabilities given equation (9). As shown in the equation (1), π_t is the inflation rate which consists of y_t^P, a random walk without drift, and the stationary component, y_t^T where it is assumed to be a deviation of y_t from the stochastic trend, y_t^P and also to be generated by a ARMA (p, q) process;

$$\pi_t = y_t^P + y_t^T \tag{1}$$

$$y_t^P = y_{t-1}^P + v_t^P \tag{2}$$

$$\phi_{S_t}(L) y_t^T = \varphi_{S_t}(L) v_t^T \tag{3}$$

$$\begin{bmatrix} v_t^P \\ v_t^T \end{bmatrix} \sim \text{ i. i. d } N\left(\begin{bmatrix} 0 \\ 0 \end{bmatrix}, \ Q_{S_t} \right) \tag{4}$$

where

$$Q_{S_t} = \begin{bmatrix} \sigma_{P,S_t}^2 & \sigma_{PT,S_t} \\ \sigma_{PT,S_t} & \sigma_{T,S_t}^2 \end{bmatrix}, \tag{5}$$

$$\phi_{S_t}(L) = 1 - \phi_{1,S_t} L^1 - \phi_{2,S_t} L^2 - \cdots - \phi_{p,S_t} L^p, \tag{6}$$

$$\varphi_{S_t}(L) = 1 + \varphi_{1,S_t} L^1 + \varphi_{2,S_t} L^2 + \cdots + \varphi_{q,S_t} L^q, \tag{7}$$

$$\sigma_{PT,S_t} = \rho_{S_t} \ \sigma_{P,S_t} \ \sigma_{T,S_t}, \tag{8}$$

and $\Pr[S_t = j \mid S_{t-1} = i] = p_{ij}$, $0 \le p_{ij} \le 1$, $\sum_{j=1}^{3} p_{ij} = 1$, $i, j \in \{1,2,3\}$ (9)

For stationarity of y_t^T, it is assumed that all roots of the polynomial, $1 - \phi_{1,S_t} X^1 - \phi_{2,S_t} X^2 - \cdots - \phi_{p,S_t} X^p = 0$ lie outside of complex unit circle. In addition, both y_t^P and y_t^T are assumed to have Markov-switching conditional variance. We also assume that the transition probability (p_{ij}) is exogenous and constant over time. We additionally take account of the correlation between permanent shock, v_t^P and transitory shock, v_t^T. Considering that the correlation between the two shocks may be reasonable, we don't constrain the model parameters to have zero correlation between shocks.

In this model specification, we consider the possibility that all hyper-parameters are

subject to regime shifts. Of all the shift parameters, the main nature to determine potential regime shifts in U.S. inflation dynamics is the change in the standard error of permanent shock, σ_{P,S_t} as well as $\phi_{S_t}(L)$.

As in Campbell and Mankiw (1987) and Fuhrer (1995), we should derive the cumulative impulse response function within the given state to identify and explicitly compare the changes in persistence over time or state. For this purpose, it should be possible for our model to be transformed into a conventional ARIMA model, which is a noteworthy property of the above model. The procedure can be summarized as follows.

$$\alpha_{S_t}(L)\Delta\pi_t = \theta_{S_t}(L)e_t, \quad e_t \sim i.i.d.N(0,\sigma^2_{S_t}) \tag{10}$$

$$\alpha_{S_t}(L) = \phi_{S_t}(L) = 1 - \alpha_{1,S_t}L^1 - \alpha_{2,S_t}L^2 - \cdots - \alpha_{p,S_t}L^p \tag{11}$$

$$\theta_{S_t}(L) = 1 + \theta_{1,S_t}L^1 + \theta_{2,S_t}L^2 + \cdots + \theta_{k,S_t}L^k \tag{12}$$

where $k = \max\{p, q+1\}$,

$$\alpha_{i,S_t} = f_\alpha(\phi_{1,S_t}, \phi_{2,S_t}, \ldots, \phi_{p,S_t}, \varphi_{1,S_t}, \varphi_{2,S_t}, \ldots, \varphi_{p,S_t}, \sigma^2_{P,S_t}, \sigma^2_{T,S_t}, \rho_{S_t}), \tag{13}$$

$$\theta_{i,S_t} = f_\theta(\phi_{1,S_t}, \phi_{2,S_t}, \ldots, \phi_{p,S_t}, \varphi_{1,S_t}, \varphi_{2,S_t}, \ldots, \varphi_{p,S_t}, \sigma^2_{P,S_t}, \sigma^2_{T,S_t}, \rho_{S_t}), \tag{14}$$

and $$\sigma^2_{S_t} = f_\sigma(\phi_{1,S_t}, \phi_{2,S_t}, \ldots, \phi_{p,S_t}, \varphi_{1,S_t}, \varphi_{2,S_t}, \ldots, \varphi_{p,S_t}, \sigma^2_{P,S_t}, \sigma^2_{T,S_t}, \rho_{S_t}) \tag{15}$$

As shown in equations (13) through (15), all of the parameters in the ARMA process can be represented by a function of the hyper parameters in the basic state-space model. In this respect, the basic model's transformation into ARIMA (p, q) implies that this state-space model approach is not at all peculiar. For detailed transformation procedure, refer to Appendix 1.

3. Estimation Results

In this section, let's apply a simplified case of $p=2$ and $q=0$ into the U.S. inflation data[5]. The sample period is 1960:I –2003:IV (observations between 1960:I-1962:II are used to obtain initial values for the filter). Figure 1 depicts the evolution of the quarterly U.S. inflation, measured as the first difference in the log of the GDP deflator, quoted annually over the period 1960:I-2003:IV.

Figure 2 simultaneously plots the estimated stochastic trend against actual U.S. inflation rate and the implied cyclical component. The estimates are conditional on information up to time t, based on Kim's algorithm.

Table 1 presents the estimates of the state-space model with a three-state Markov-switching as a basic model. Of special interest are the estimates of the standard error of the permanent shock (σ_{P,S_t}). σ_{P,S_t} is significantly different from zero over all states. Thus, shocks within the U.S. inflation rate have had both permanent and transitory effects on the inflation level, as opposed to the findings of Leybourne, Kim and Newbold (2003) and Kim (2000). In particular, it is noticeable that estimates of σ_{P,S_t} are markedly different across states, which crucially influences efforts to determine the extent of inflation persistence across regimes.

The estimates of the transition probabilities to govern the dynamics of S_t indicate that all states are appreciably persistent. The probability of remaining in state 1, state 2 and state 3 from one quarter to the next is about 97 percent, 98 percent and almost 100 percent, respectively.

Table 3 reports reduced parameter estimates transformed into ARIMA (2,1,2) for each

[5] In case $p=1$, the null hypothesis that the residuals aren't serially correlated couldn't rejected; the case of $p=2$ satisfied the assumption there is neither serial correlation nor heteroskedasticity as shown in Table 2. In addition, the model specification of $p=2$ was superior to the other cases in the respect of AIC or SIC.

regime. Figure 3 summarizes the impulse response of the inflation rate to one-unit shock across 3 states, calculated from the results in Table 3. One of the most important features is that the long-run response under state 2 is much higher than under the other states. In addition, the long-run response under state 1 is relatively high compared with state 3, which is consistent with Bleany's (2001) empirical finding that persistence in 1984-99 was estimated to be higher than in 1954-72.

More detailed estimation results across all states are also shown in Figure 3a, 3b and 3c, where ±1.96 standard error bands are plotted, yielding an approximate 95 percent confidence interval for each of the impulse responses. One of the most noteworthy points is that, of all three cumulative impulse response functions, only state 2 shows inflation as permanently changed by the shock with statistical significance as shown in Figure 3b. However, the other dynamic responses were not statistically different from zero over the horizon because their confidence bands included the zero line. These findings explicitly demonstrate that U.S. inflation was substantially persistent in regime 2, the period corresponding to state 2. But U.S. inflation persistence was much less under regimes 1 and 3, than it was under regime 2; even though the positive shock also had a positive long-run effect on inflation under regimes 1 and 3, the effect was reversed to less than 0.25 after one or two quarters.

What period then corresponds to regimes 1, 2 or 3? Figure 4a depicts filtered probability, $\Pr[S_t = 1 | I(t)]$ and smoothed probability, $\Pr[S_t = 1 | I(T)]$ based on Kim's algorithm. That is, Figure 4a shows the estimated probabilities that inflation is in its lowest persistence state based on current information, $I(t)$ and full information, $I(T)$. Similarly, Figures 4b and 4c show filtered and smoothed probabilities of highest persistence and medium persistence regimes, respectively. From the above figures, we find that inflation entered a high persistence state, regime 2, around the late 1960's — abandonment of the Bretton Woods system — and then started to fall back to the medium persistence state, regime 3, in the early 1980's — the beginning of the Volker-

Greenspan era. Thus, we can without any difficulty infer that over the period 1960:I-2003:IV, the inflation dynamics had two structural changes as shown in Figures 4a, 4b and 4c. But when are the exact regime change points? To estimate them and make inferences on that issue, we should allow a restriction on the basic model as follows;

$$p_{13} = p_{21} = p_{31} = p_{32} = 0 \tag{16}$$

$$\text{where} \quad \Pr[S_t = j \mid S_{t-1} = i] = p_{ij}, \quad 0 \le p_{ij} \le 1, \quad \sum_{j=1}^{3} p_{ij} = 1, \quad i, j \in \{1,2,3\} \tag{17}$$

This (16) specifies two permanent structural breaks in the dynamics of U.S. inflation after the Korean War, where the expected durations of regimes 1 and 2 are given by $1/(1-p_{11})$ and $1/(1-p_{22})$.

The estimated results of structural breaks at unknown date are also shown in Table 4. Firstly, we must point out that there is little difference between the unrestricted model and the restricted model, with regard to their likelihood values. Taking those estimated results into consideration, therefore, we can be more convinced that the U.S. inflation dynamics passed through the three kinds of regime in order. Secondly, the first structural change point was estimated at 1972:I and the second at 1985:III, while both regime changes already began in the late 1960's and the early 1980's. These findings can be also seen in Figure 5, which plots the conditional probability of the first and the second structural break at time t based on full information up to time T, $\Pr[Sb_t = 1st \mid I(T)]$ and $\Pr[Sb_t = 2nd \mid I(T)]$, derived from the estimated results of $\Pr[S_t = i \mid I(T)]$ in terms of i =1 and 2, respectively.

Thus, as far as the change points are concerned, although the estimates are similar to Evans and Wachtel's (1993) and B-S's (1999) findings that there was an upward shift in persistence in 1974 and a downward shift in 1982, this paper supports Bleaney's (2001) and A-S's

(1991) view in terms of the implication of the estimation results, which will be discussed in the following section.

4. Source of changes in inflation persistence and the Lucas Critique

The estimation results of the basic state-space model with Markov-switching and two permanent structural breaks model provide empirical evidence that changes in U.S. inflation persistence over time have happened at least twice.

How then can we explain those changes? To investigate why U.S. inflation exhibited relatively higher persistence in the 1970s rather than in the 1960s and 1990s, several representative theoretical explanations have been employed.

A-S (1991) and Bleaney (2001) found evidence that monetary accommodation existed under floating rates rather more significantly than under fixed rates, although monetary policy would not necessarily be more accommodating under floating rates. Another explanation is the double oil crises (Evans (1991), B-S (1999)). In particular, B-S (1999) argued that the historical shifts in inflation persistence were more associated with oil shocks than exchange rate regime changes. The other is the degree of central bank independence or the way the central bank performs its policies. Firstly, Clarida, Gali and Gertler (1998) showed that post-1979 interest rate reaction function had a higher inflation coefficient, which should imply smaller monetary accommodation of inflation. Papadopoulos and Sidiropoulos (2000) provided theoretical arguments with empirical evidence for the rationale that low inflation persistence might be obtained by improving central bank independence. Furthermore, Erceg and Levin (2001) insisted that inflation persistence is not an inherent characteristic of the economy, but rather varies with

the stability and transparency of the monetary policy regime. They argued that inflation persistence is generated when private agents have limited information about the central bank's objectives, which cause the output costs of disinflation. They also suggested empirical evidence that their theoretical finding can account quite well for the dynamics of inflation during the Volker disinflation.

However, Kim and Nelson (1999) and McConnell and Quiros (1999) discussed the fact that the real U.S. GDP growth had become more stable since the mid 1980s than it had been before. Their findings may indicate that stabilization in U.S. inflation from the mid 1980s onwards should be regarded as not a unique phenomenon, but rather one of structural declines in the volatility of the U.S. economy. With regard to the counteraction between output and inflation, Fuhrer and Moore (1995) argued that using Taylor's (1980) overlapping wage contracts model would ensure that the persistence in inflation was theoretically derived from that of output growth, even without its own persistence. This also holds true for the correlation between inflation and lagged output[6]. In addition, Dittmar, Gavin and Fydland (2003) showed that, in cases where the central bank induces a persistent difference between the nominal and real interest rates, inflation persistence can theoretically exist even under flexible prices economy.

Among the explanations above, this paper focuses on the A-S's (1991) and Bleany's (2001) suggestions that the regime shifts are correlated with the changes in the international exchange rate system and monetary policy rule.

Concerning the upward shifts in persistence, they suggested that the exchange rate regime changed from the pegged to the floating, or managed, as a result of the collapse of Bretton Woods

[6] However, when measured by its autocorrelation function and its cross correlations with real output, the inflation showed quite persistence. Therefore, the data favored the relative contracting model in which the inflation persistence is generated by both its own and output dynamics unlike in the standard model of Taylor (1980)

system,[7] as mentioned above. To be illustrated, if positive inflation shock occurs, it will increase the price level and lead to depreciation of the domestic currency. The depreciation causes a rise in import prices, which will in turn increase domestic inflation. In this way, the inflation shock becomes persistent to a certain extent. Under the fixed exchange rate regime, however, inflation shock does not have as much of an effect on inflation levels as under the floating rate regime of the trinity impossibility.

Let's consider a case in which negative supply shock occurs in the economy. Monetary authorities would trigger inflation in order to offset some part of the shock's effect on output under the floating rate system, which is consistent with minimization of the conventional social loss function. But because such supply shocks are serially correlated, inflation keeps going for a certain period. In this situation, however, monetary authorities' countenance is almost impossible under the fixed rate system. Especially in cases where monetary authorities perform a PPP-oriented exchange rate policy, it tends to maintain the real exchange rate constant, thus stabilizing demand, which in turn leads to instability of prices and high persistence in inflation[8]. Intuitively, inflation persistence under the floating rate regime is more apt to increase compared with under the fixed rate.

Even under the flexible rate system, the extent of inflation persistence depends on how accommodative the monetary policy is. The higher the monetary accommodation, the more persistent inflation rate gets. A price shock raises expectations that the unemployment rate will become lower under higher accommodative monetary policy regime than under absence of accommodation. This generates expectations of higher current and future nominal wages, which induces firms to set their initial price higher to try to smooth price rises, as in A-S (1991). In

[7] A-S (1991), Alogoskoufis (1992), Dornbush (1982), Bleaney (2001)
[8] Dornbush (1982)

contrast, the lower the monetary accommodation, the less persistent the inflation rate.

After the Volker era, the monetary accommodation has been weaker, which is also supported by Clarida, Gali and Gertler (1998). Therefore, the downward shift in persistence in the early 1980s is deeply influenced by less monetary accommodation than before, even under the flexible rate system. Besides monetary accommodation, we shouldn't exclude other possibilities. As Erceg and Levin (2001) pointed out, the policy credibility and transparency might have a substantial effect in that those factors could also be determinants of inflation persistence. For this reason, Bordo and Haubrich (2004) recently measured the performance and credibility of monetary regimes as the persistence of inflation. They postulated that inflation showed little persistence in credible regimes such as the gold standard era, while in less credible regimes such as the post Bretton Woods era, it was more persistent.

To sum up, according to the first regime switching, the exchange rate regime change from fixed rates to flexible rates in the late 1960s played a major role in provoking high persistence in U.S. inflation. For the second, it was reported that improvements in the operating ability of the monetary policy after the Volker-Greenspan era in the early 1980s led to the regime shifts in the inflation dynamics or persistence. As a consequence, these estimation results are consistent with the theory to interpret the changes in inflation persistence as the regime shifts associated with exchange rate systems and the monetary policy stance, in which the Lucas Critique implies.

5. Conclusion

In presenting a state-space model with Markov-switching, we have shown that there are significant shifts in U.S. inflation persistence by deriving cumulative impulse response function

over time. The distinctive feature of our model is to consider double regime shifts and heteroskedasticity under unknown change points. Moreover, we did not impose the restriction that the U.S. inflation followed a stationary process throughout the period.

The estimation results are as follows. Firstly, the starting point of the first structural change in the inflation process coincided with exchange rate system shift from fixed rates to flexible rates led by the abandonment of Bretton Woods system in the late 1960s. According to the second breakpoint, the starting point was substantially associated with the central bank's monetary policy regime switching in the Volker-Greenspan era in the early 1980s. These empirical evidences suggest that regime switches in U.S. inflation persistence could have been caused by the Lucas Critique based on the existing theoretical background.

These findings have an important implication that under flexible exchange rates, inflation is more vulnerable to the upward shifts in persistence rather than under fixed rates. Especially if monetary authorities do not make a positive effort to be less accommodative by keeping policy transparency and credibility, they will be confronted with considerable difficulties in controlling the inflation at some level. Therefore, the current monetary policy has been carried out at the risk of higher persistence than before the late 1960s. In this sense, those points shouldn't be disregarded for disinflation policy not to cost severe output loss.

<Appendix >

This appendix consists of two parts. The first deals with the transformation process from a state-space model to a conventional ARIMA model and the second is concerned with how to construct log likelihood function for approximate MLE.

I. Model Transformation

As mentioned in the text, those state-space representations can easily be transformed into a conventional ARIMA specification. That implies that parameters in state-space representation describe those in ARIAM specification through the following process. We consider the Model II.

$S_t \in \{1,2,3\}$

$$\pi_t = y_t^P + y_t^T \tag{a1}$$

$$y_t^P = y_{t-1}^P + v_t^P \tag{a2}$$

$$\phi_{S_t}(L) y_t^T = \varphi_{S_t}(L) v_t^T \tag{a3}$$

$$\begin{bmatrix} v_t^P \\ v_t^T \end{bmatrix} \sim \text{ i. i. d } N\left(\begin{bmatrix} 0 \\ 0 \end{bmatrix}, Q_{S_t} \right) \tag{a4}$$

$$Q_{S_t} = \begin{bmatrix} \sigma_{P,S_t}^2 & \sigma_{PT,S_t} \\ \sigma_{PT,S_t} & \sigma_{T,S_t}^2 \end{bmatrix} \tag{a5}$$

$$\phi_{S_t}(L) = 1 - \phi_{1,S_t} L^1 - \phi_{2,S_t} L^2 - \cdots - \phi_{p,S_t} L^p \tag{a6}$$

$$\varphi_{S_t}(L) = 1 + \varphi_{1,S_t} L^1 + \varphi_{2,S_t} L^2 + \cdots + \varphi_{q,S_t} L^q \tag{a7}$$

For $S_t = j$, from (a1) and (a2)

$$\Delta\pi_t = \phi_{1,S_t}\Delta\pi_{t-1} + \phi_{2,S_t}\Delta\pi_{t-2} + v_t^P - \phi_{1,S_t}v_{t-1}^P - \phi_{2,S_t}v_{t-2}^P + v_t^T + v_{t-1}^T = \phi_{1,S_t}\Delta\pi_{t-1} + \phi_{2,S_t}\Delta\pi_{t-2} + u_t$$

where $u_t = v_t^P - \phi_{1,S_t}v_{t-1}^P - \phi_{2,S_t}v_{t-2}^P + v_t^T + v_{t-1}^T$. (a8)

Then, u_t is a MA(2) process. Thus,

$$\Delta\pi_t = \phi_{1,S_t}\Delta\pi_{t-1} + \phi_{2,S_t}\Delta\pi_{t-2} + u_t = \alpha_{1,S_t}\Delta\pi_{t-1} + \alpha_{2,S_t}\Delta\pi_{t-2} + e_t + \theta_{1,S_t}e_{t-1} + \theta_{2,S_t}e_{t-2} \quad \text{(a9)}$$

$$\alpha_{S_t}(L)\Delta\pi_{t-1} = \theta_{S_t}(L)e_t \quad \text{(a10)}$$

where $e_t \sim i.i.d.N(0,\sigma_{S_t}^2)$ and $u_t = e_t + \theta_{1,S_t}e_{t-1} + \theta_{2,S_t}e_{t-2} = \theta_{S_t}(L)e_t$. (a11)

Straightforwardly,

$$\phi_{S_t}(L) = \alpha_{S_t}(L) = 1 - \phi_{1,S_t}L - \phi_{2,S_t}L^2 = 1 - \alpha_{1,S_t}L - \alpha_{2,S_t}L^2. \quad \text{(a12)}$$

From (a8), unconditional mean, variance and auto-covariance for u_t are the following:

$$E(u_t) = 0, \quad \text{var}(u_t) = (1 + \phi_{1,S_t}^2 + \phi_{2,S_t}^2)\sigma_{P,S_t}^2 + 2\sigma_{T,S_t}^2 + \sigma_{PT,S_t}(1 + \phi_{1,S_t}) \quad \text{(a13)}$$

$$\text{cov}(u_t, u_{t-1}) = (\phi_{1,S_t}\phi_{2,S_t} - \phi_{1,S_t})\sigma_{P,S_t}^2 - \sigma_{T,S_t}^2 + \sigma_{PT,S_t}(\phi_{2,S_t} - 1 - \phi_{1,S_t}) \quad \text{(a14)}$$

$$\text{cov}(u_t, u_{t-2}) = -\phi_{2,S_t}(\sigma_{P,S_t}^2 + \sigma_{PT,S_t}) \quad \text{(a15)}$$

$$\text{cov}(u_t, u_{t-k}) = 0 \quad \text{for all} \quad k \geq 3 \quad \text{(a16)}$$

Also from (a9),

$$E(u_t) = 0, \quad \text{var}(u_t) = (1 + \theta_{1,S_t}^2 + \theta_{2,S_t}^2)\sigma_{S_t}^2, \quad \text{(a17)}$$

$$\text{cov}(u_t, u_{t-1}) = \theta_{1,S_t}(1 + \theta_{2,S_t})\sigma_{S_t}^2 \quad \text{(a18)}$$

$$\text{cov}(u_t, u_{t-2}) = \theta_{2,S_t}\sigma_{S_t}^2 \quad \text{(a19)}$$

$$\mathrm{cov}(u_t, u_{t-k}) = 0 \quad \text{for all} \quad k \geq 3 \tag{a20}$$

Thus, since both in case u_t is characterized with v_t^P and v_t^T and in case with e_t, they should be equivalent,

$$\mathrm{var}(u_t) = (1 + \phi_{1,S_t}^2 + \phi_{2,S_t}^2)\sigma_{P,S_t}^2 + 2\sigma_{T,S_t}^2 + \sigma_{PT,S_t}(1 + \phi_{1,S_t}) = (1 + \theta_{1,S_t}^2 + \theta_{2,S_t}^2)\sigma_{S_t}^2 \tag{a21}$$

$$\mathrm{cov}(u_t, u_{t-1}) = (\phi_{1,S_t}\phi_{2,S_t} - \phi_{1,S_t})\sigma_{P,S_t}^2 - \sigma_{T,S_t}^2 + \sigma_{PT,S_t}(\phi_{2,S_t} - 1 - \phi_{1,S_t}) = \theta_{1,S_t}(1 + \theta_{2,S_t})\sigma_{S_t}^2 \tag{a22}$$

$$\mathrm{cov}(u_t, u_{t-2}) = -\phi_{2,S_t}(\sigma_{P,S_t}^2 + \sigma_{PT,S_t}) = \theta_{2,S_t}\sigma_{S_t}^2 \tag{a23}$$

The parameters for u_t in state-space representation are three in total, σ_{P,S_t}^2, σ_{T,S_t}^2 and σ_{PT,S_t} where ϕ_{1,S_t} and ϕ_{2,S_t} are excluded. Those for u_t in ARIMA form are still three, θ_{1,S_t}, θ_{2,S_t} and $\sigma_{S_t}^2$. Therefore, we are able to make an inference about parameters in ARIMA process by solving the simultaneous equations through (a21) to (a23). In this way, we can also derive the impulse response function across the regimes in order to verify changes in U.S. inflation persistence.

II. Construction of Likelihood Function

A state-space representation of the model in this paper is given by the following two equations;

Measurement equation

$$\pi_t = \begin{bmatrix} 1 & 1 & 0 \end{bmatrix} \begin{bmatrix} y_{1t} \\ y_{2t} \\ y_{2t-1} \end{bmatrix} = H\ \beta_t + E_t\,, \tag{a24}$$

where $H = \begin{bmatrix} 1 & 1 & 0 \end{bmatrix}$, $E(E_t E_t') = R_j = 0$ for all t and $j = 1, 2, \cdots, \mathrm{M}$.

Transition equation

$$\beta_t = \begin{bmatrix} y_{1t} \\ y_{2t} \\ y_{2t-1} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \phi_{1,j} & \phi_{2,j} \\ 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} y_{1t-1} \\ y_{2t-1} \\ y_{2t-2} \end{bmatrix} + \begin{bmatrix} v_t^P \\ v_t^T \\ 0 \end{bmatrix} = F_j\ \beta_{t-1}\ +\ V_t \tag{a25}$$

$$V_t = \begin{bmatrix} v_t^P \\ v_t^T \\ 0 \end{bmatrix} \sim \text{i. i. d}\ N\left(\begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix},\ Q_j \right), \quad Q_{S_t} = \begin{bmatrix} \sigma_{P,j}^2 & \sigma_{PT,j}^2 & 0 \\ \sigma_{PT,j}^2 & \sigma_{T,j}^2 & 0 \\ 0 & 0 & 0 \end{bmatrix} \tag{a26}$$

Then, if $\beta_{t-1|t-1}^j$ and $p_{t-1|t-1}^j$ are given, the marginal density of π_t is obtained based on the prediction error decomposition by

$$f(\pi_t \,|S_{t-1}, S_t, I_{t-1}) = 2\pi \left| f_{t|t-1}^{(i,j)} \right|^{-0.5} \exp\{-\frac{1}{2} \eta_{t|t-1}^{(i,j)}{}' f_{t|t-1}^{(i,j)^{-1}} \eta_{t|t-1}^{(i,j)}\}\,, \quad (i, j = 1, 2, \ldots, \mathrm{M}) \tag{a27}$$

where

$$\beta_{t|t-1}^{(i,j)} = E[\beta_t \,|I_{t-1}, S_t = j, S_{t-1} = i] = F_j\ \beta_{t-1|t-1}^j\,, \tag{a27}$$

$$p_{t|t-1}^{(i,j)} = E[(\beta_t - \beta_{t|t-1})(\beta_t - \beta_{t|t-1})' |I_{t-1}, S_t = j, S_{t-1} = i] = F_j\ p_{t-1|t-1}^j\ F_j' + Q_j\,, \tag{a28}$$

$$\eta_{t|t-1}^{(i,j)} = \ \pi_t - H\ \beta_{t|t-1}^{(i,j)} \ \ (= \text{the conditional forecast error of } \pi_t), \tag{a29}$$

and $f_{t|t-1}^{(i,j)} = H\ \ p_{t-1|t-1}^{(i,j)}\ H' + R_j$ (= the conditional variance of forecast error, $\eta_{t|t-1}^{(i,j)}$). (a30)

When $\Pr(S_{t-1}|I_{t-1})$ is also given,

$$\Pr[S_t = j, S_{t-1} = i|I_{t-1}] = \Pr[S_t = j|S_{t-1} = i]\ \Pr[S_{t-1}|I_{t-1}]. \tag{a31}$$

Then, Log Likelihood is derived as

$$\text{LL} = \sum_{t=1}^{T} \ln[f(\pi_t|I_{t-1})] \tag{a32}$$

where $f(y_t|I_{t-1}) = \sum_{j=1}^{M}\sum_{i=1}^{M} f(\pi_t, S_t = j, S_{t-1} = i|I_{t-1})$

$$= \sum_{j=1}^{M}\sum_{i=1}^{M} f(\pi_t|I_{t-1}, S_t = j, S_{t-1} = i)\ \Pr[S_t = j, S_{t-1} = i|I_{t-1}] \tag{a33}$$

and the log likelihood function can be maximized with respect to ϕ_{1,S_t}, ϕ_{2,S_t}, σ_{P,S_t}, σ_{T,S_t}, ρ_{S_t}, p_{11}, p_{12}, p_{21}, p_{22}, p_{31} and p_{32}. In order to make the above Kalman filter operable, some approximations need to be employed such as follows.

$$\beta_{t|t}^{(i,j)} = E[\beta_t\ |I_t, S_t = j, S_{t-1} = i] = \beta_{t|t-1}^{(i,j)} + p_{t|t-1}^{(i,j)}\ H'[f_{t|t-1}^{(i,j)}]^{-1}\ \eta_{t|t-1}^{(i,j)}, \tag{a34}$$

$$p_{t|t}^{(i,j)} = E[(\beta_t - \beta_{t|t-1})(\beta_t - \beta_{t|t-1})'|I_t, S_t = j, S_{t-1} = i] = p_{t|t-1}^{(i,j)} - p_{t|t-1}^{(i,j)}\ H'[f_{t|t-1}^{(i,j)}]^{-1}\ H\ p_{t|t-1}^{(i,j)}, \tag{a35}$$

$$\beta_{t|t}^{j} = E[\beta_t\ |I_t, S_t = j] = \frac{\sum_{i=1}^{M} \Pr[S_t = j, S_{t-1} = i|I_t]\beta_{t|t}^{(i,j)}}{\Pr[S_t = j|I_t]} \tag{a36}$$

and $p_{t|t}^{j} = E[(\beta_t - \beta_{t|t}^{j})(\beta_t - \beta_{t|t}^{j})'|I_t, S_t = j]$ (a37)

$$= \frac{\sum_{i=1}^{M} \Pr[S_t = j, S_{t-1} = i|I_t][P_{t|t}^{(i,j)} + (\beta_{t|t}^{j} - \beta_{t|t}^{(i,j)})(\beta_{t|t}^{j} - \beta_{t|t}^{(i,j)})']}{\Pr[S_t = j|I_t]}. \tag{a38}$$

For further details, refer to Chapter 5 in Kim and Nelson (1999).

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Table 1

Maximum Likelihood Estimates of a State-Space Model with a Three-State Markov-Switching ($p=2$ and $q=0$)

	$S_t=1$	$S_t=2$	$S_t=3$
ϕ_{1,S_t}	0.2469 (0.2510)	0.0638 (0.3078)	-0.1470 (0.1634)
ϕ_{2,S_t}	-0.3829 (0.2417)	-0.5439 (0.3847)	-0.1857 (0.1853)
σ_{P,S_t}	0.3723 (0.1142)	1.1627 (0.2993)	0.2893 (0.0685)
σ_{T,S_t}	0.4848 (0.1300)	0.4106 (0.2336)	0.4704 (0.0787)
ρ_{S_t}	0.9937 (0.1771)	0.9935 (0.0362)	0.9937 (0.1834)
p_{11}		0.9734 (0.0264)	
p_{12}		0.0265 (0.0264)	
p_{21}		2.26-7 (0.0002)	
p_{22}		0.9816 (0.0184)	
p_{31}		8.92e-8 (6.34e-5)	
p_{32}		1.05e-7 (2.46e-5)	
Log Likelihood		-237.4759	

Note: Standard errors are in parentheses.

Table 2
Residual Tests Using Box-Pierce-Ljung Statistics

Lag	1	2	3	4	5	6	7	8	9	10
Standardized Residual	0.942 (0.331)	1.465 (0.480)	2.654 (0.448)	6.090 (0.192)	6.370 (0.271)	6.381 (0.381)	6.461 (0.487)	7.039 (0.532)	9.150 (0.423)	9.212 (0.512)
Standardized and squared residual	0.441 (0.506)	0.526 (0.768)	1.107 (0.775)	1.110 (0.892)	1.115 (0.952)	2.073 (0.912)	4.686 (0.698)	4.734 (0.785)	6.991 (0.637)	7.030 (0.722)

Note: Figures in parentheses are p-values

Table 3
Estimates of ARIMA Model Transformed from the Basic State-Space Model

	$S_t = 1$	$S_t = 2$	$S_t = 3$
α_{1,S_t}	0.2469 (0.2510)	0.0638 (0.3078)	-0.1470 (0.1634)
α_{2,S_t}	-0.3829 (0.2417)	-0.5439 (0.3847)	-0.1857 (0.1853)
θ_{1,S_t}	-1.2776 (0.4765)	-0.3832 (0.2938)	-0.8117 (0.4023)
θ_{2,S_t}	0.3711 (0.5101)	0.5568 (0.5634)	0.1050 (0.1010)
$\sigma^2_{S_t}$	0.3281 (0.2806)	1.7841 (0.5213)	0.3871 (0.1338)
Long run Multiplier at Regime 1		0.0823 (0.1656)	
Long run Multiplier at Regime 2		0.7928 (0.2608)	
Long run Multiplier at Regime 3		0.2200 (0.3032)	

Note: Standard errors are in parentheses and derived by delta method.

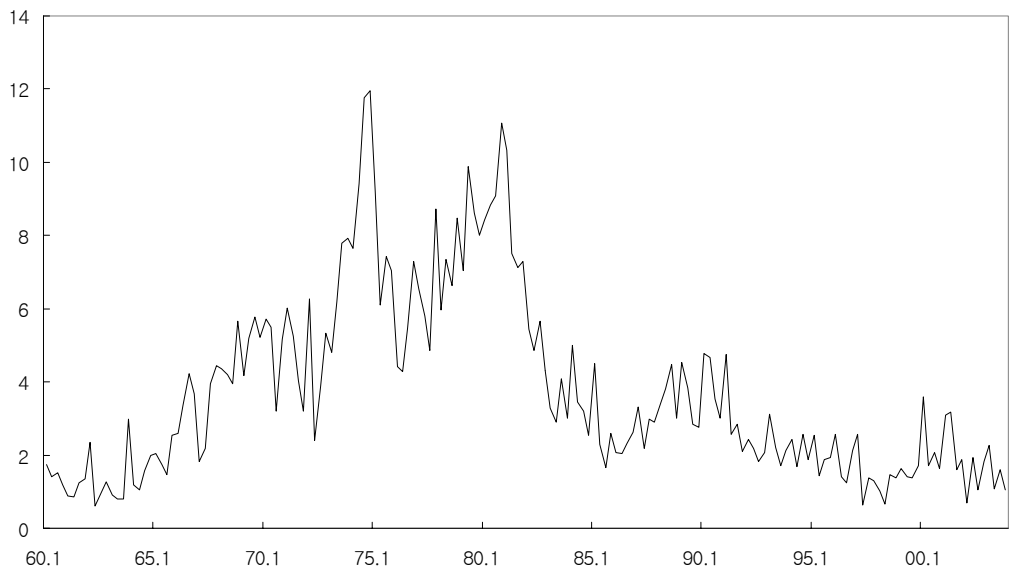
Table 4
Estimation Result of Two Permanent Structural Changes Model

	$S_t = 1$	$S_t = 2$	$S_t = 3$
ϕ_{1,S_t}	0.2469 (0.2361)	0.0638 (0.2454)	-0.1470 (0.1584)
ϕ_{2,S_t}	-0.3829 (0.2328)	-0.5441 (0.3358)	-0.1856 (0.1839)
σ_{P,S_t}	0.3722 (0.1140)	1.1627 (0.2365)	0.2893 (0.0683)
σ_{T,S_t}	0.4849 (0.1292)	0.4106 (0.1925)	0.4704 (0.0741)
ρ_{S_t}	0.9937 (0.1132)	0.9935 (0.0189)	0.9937 (0.0834)
p_{11}		0.9734 (0.0264)	
p_{22}		0.9816 (0.0184)	
Log Likelihood		-237.475	

Note: Standard errors are in parentheses and derived by delta method.

Figure 1

U.S. GDP Deflator Inflation (1960:I-2003:IV)



Source: U.S. Department of Commerce: Bureau of Economic Analysis

Figure 2
U.S. Inflation Rate, Stochastic Trend and Transitory Component

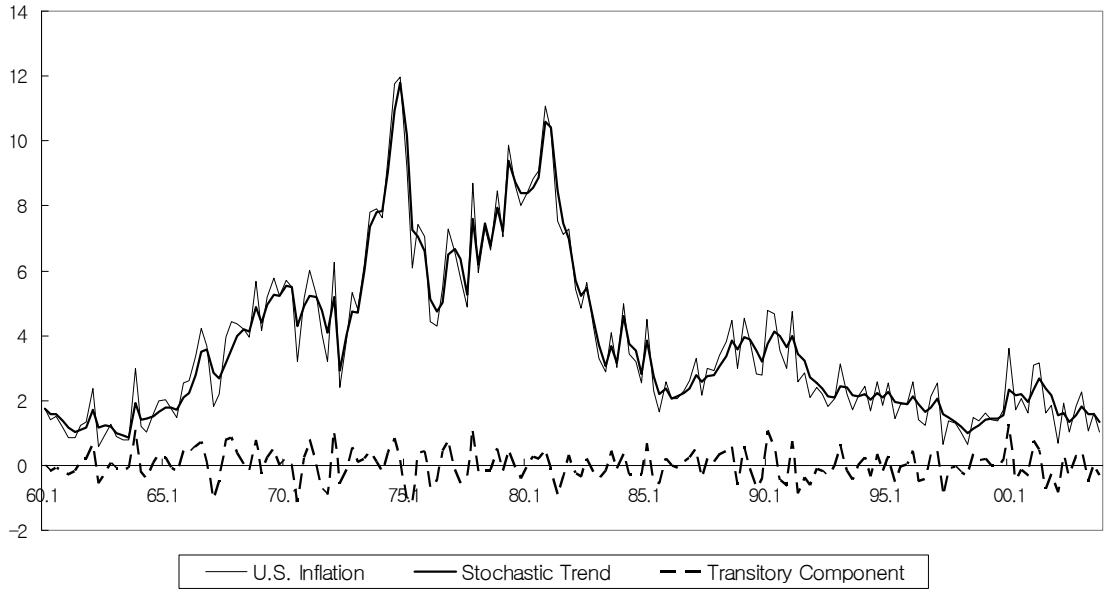


Figure 3
Impulse Response Over States

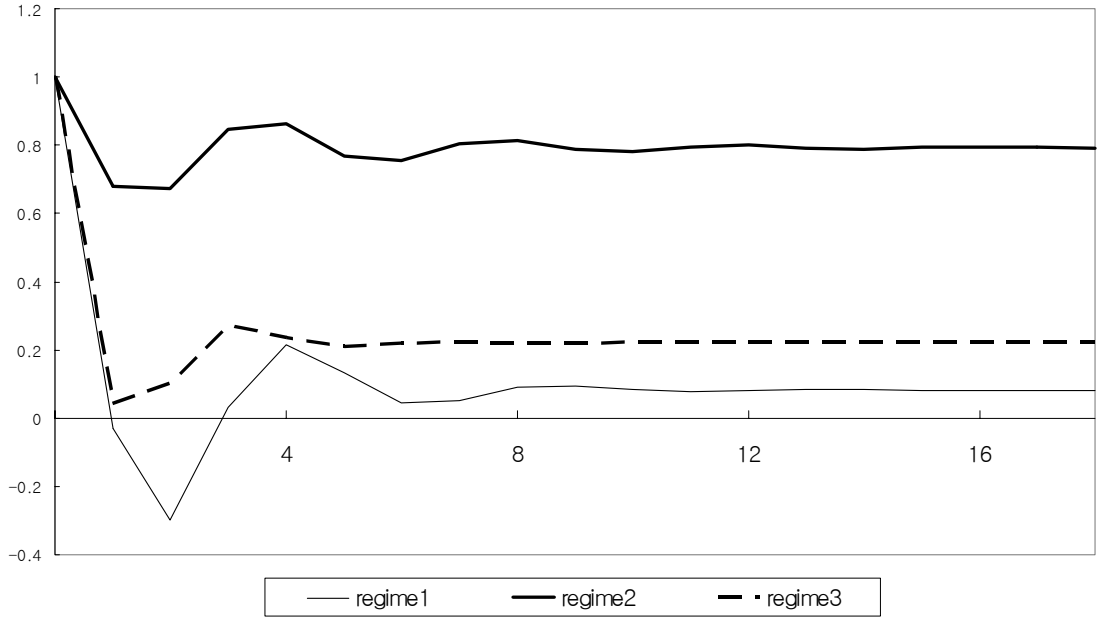


Figure 3a Cumulative Impulse Response Under State 1

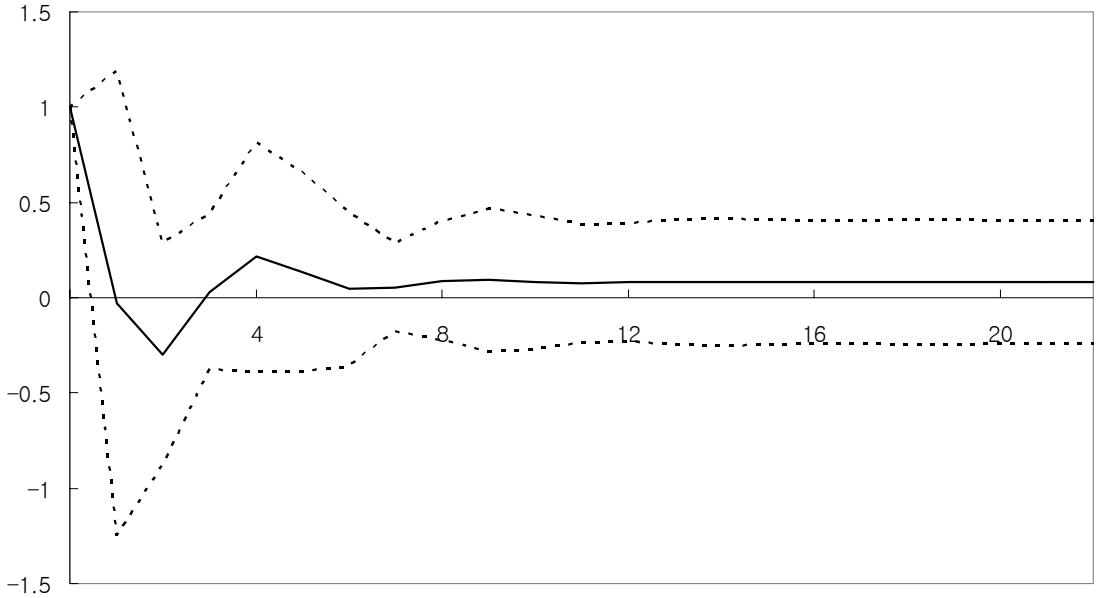


Figure 3b Cumulative Impulse Response Under State 2

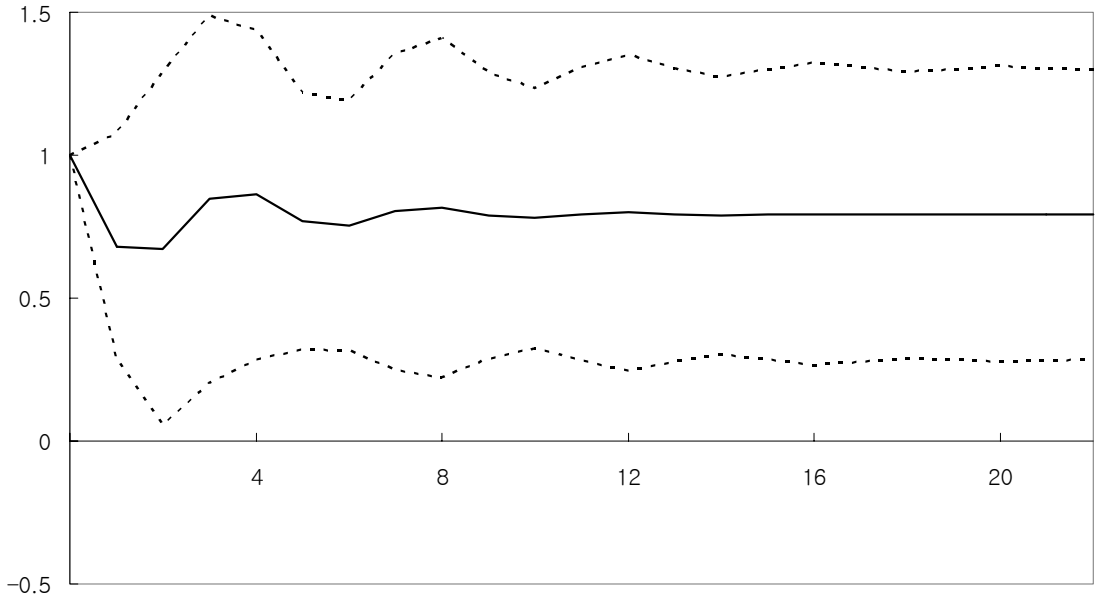


Figure 3c Cumulative Impulse Response Under State 3

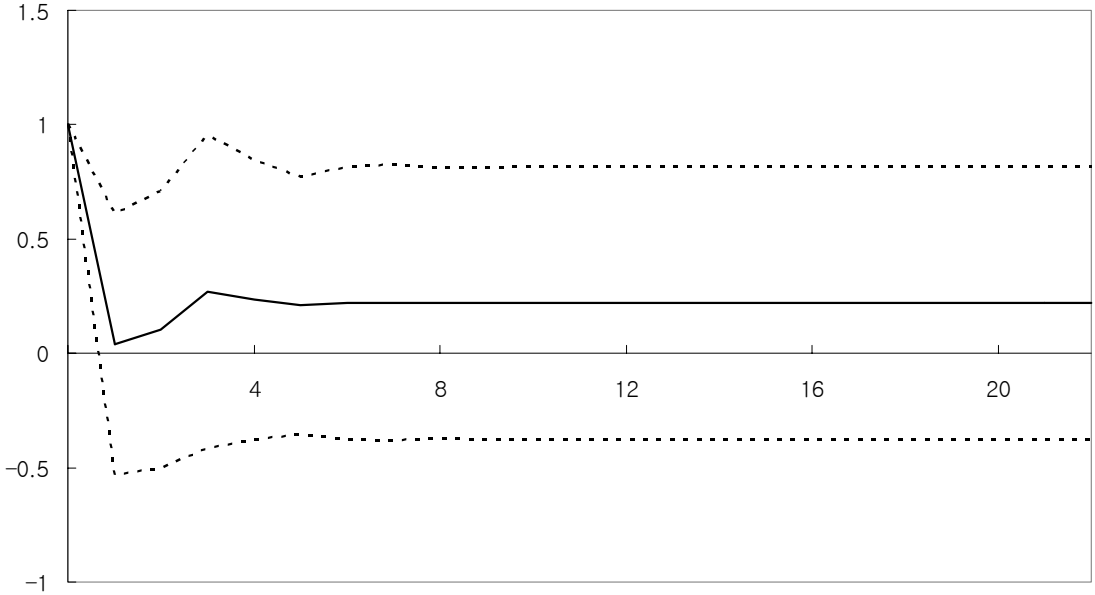


Figure 4a
Filtered and Smoothed Probabilities of a Regime with Low Long-Run Impulse Response

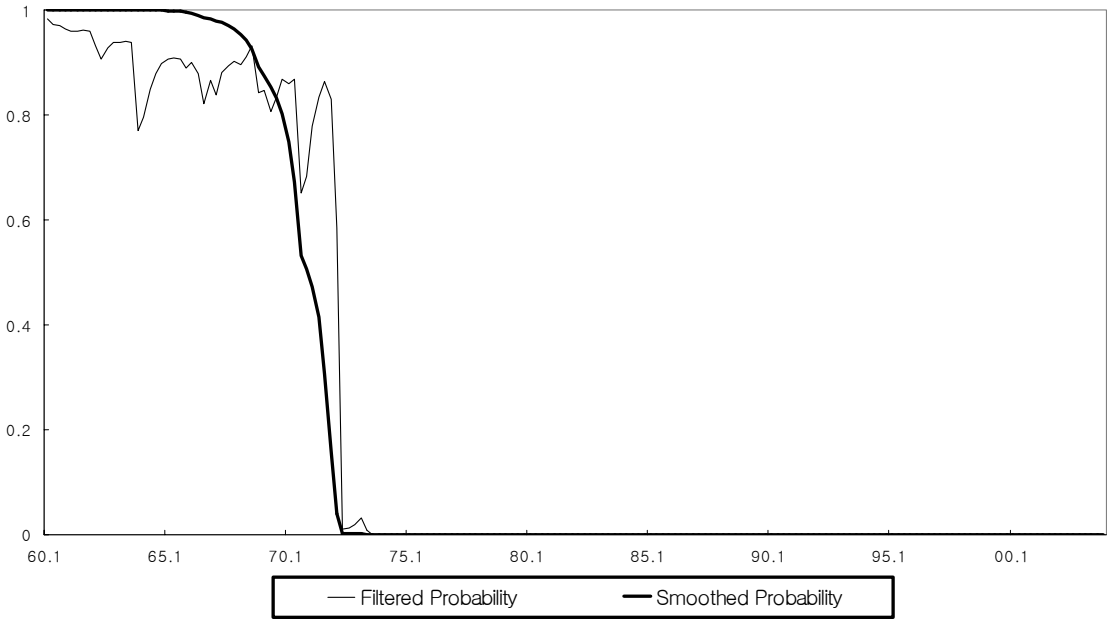


Figure 4b
Filtered and Smoothed Probabilities of a Regime with High Long-Run Impulse Response

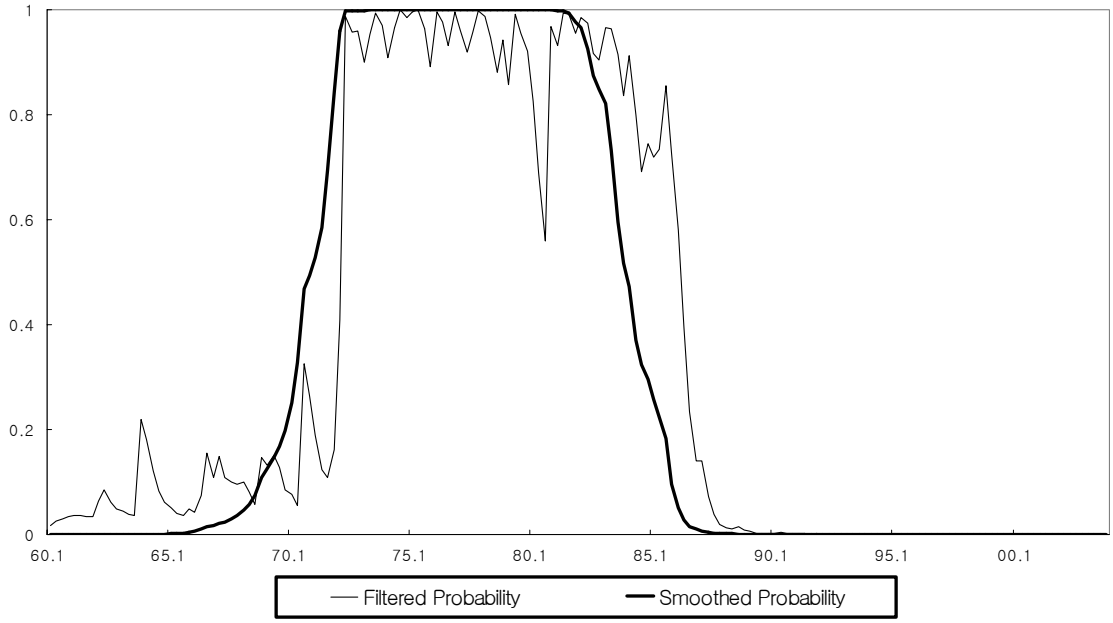


Figure 4c
Filtered and Smoothed Probabilities of a Regime with Medium Long-Run Impulse Response

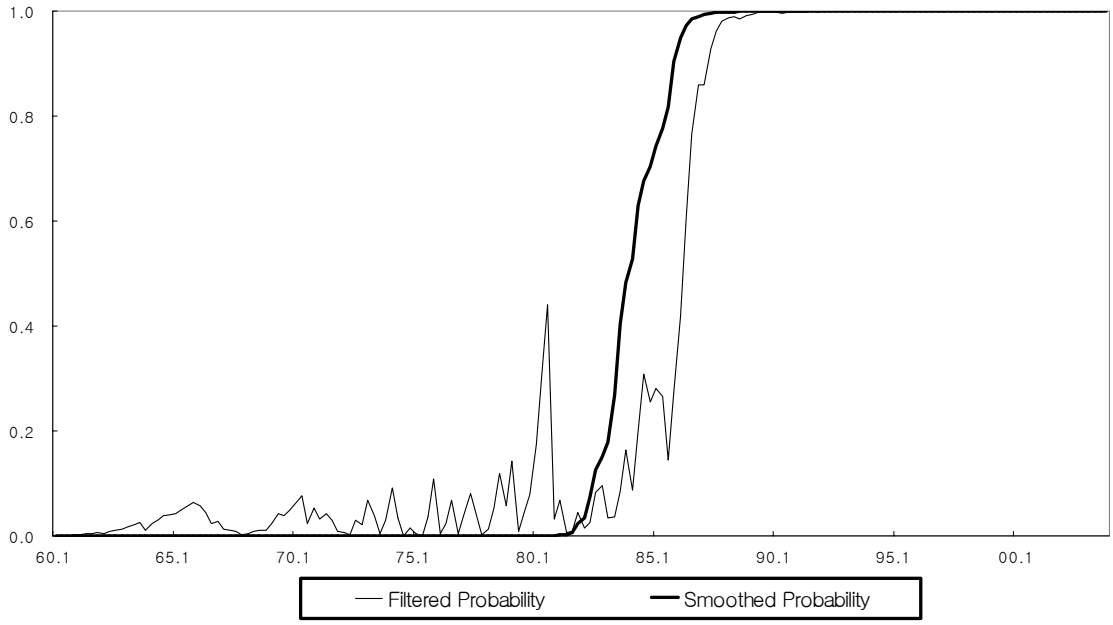


Figure 5
Actual U.S. Inflation Rate and Posterior Distributions of Break date